

**CHARMONIUM INTERACTION IN NUCLEAR MATTER****D. Kharzeev and H. Satz**Theory Division, CERN  
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and

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D-33501 Bielefeld, Germany**Abstract:**

We analyse the kinematic regimes attainable for  $J/\psi$  and  $\psi'$  production in  $p - A$  collisions. With this information, we specify the requirements for an experiment to study the interaction of physical charmonium states in nuclear matter, making use of a heavy ion beam incident on a hydrogen or deuterium target.

## 1. Introduction

The production of charmonium states in hadron-nucleus and nucleus-nucleus collisions provides an excellent tool to study different aspects of strongly interacting matter. At high energy, charmonium production proceeds through gluon fusion to a colour octet  $c\bar{c}$  state (Fig. 1a), which subsequently neutralises its colour and obtains the right quantum numbers by interacting with the colour field of the collision [1]. At lower energies, quark-antiquark annihilation adds significant contributions (Fig. 1b), which for large  $|x_F|$  become dominant. In both parton processes, the first production stage is a colour octet  $c\bar{c}$  state which needs a certain time before it becomes colour neutral. Consider  $p-A$  collisions leading to the production of charmonia fast in the rest frame of the target nucleus. The nuclear medium then sees only the passage of a fast coloured  $c\bar{c}$  pair, with which it interacts as with any colour charge. There is nothing charmonium-specific about this interaction, and in particular, the nucleus does not know what hadronic state this pair will turn into later on. To study the effect of the medium on the different physical charmonium states, these have to be sufficiently slow to be fully formed inside the medium. In the first part of this note, we will identify the kinematic regions corresponding to these different situations. As we shall show, all hadron-nucleus collisions studied so far provide information only about the passage of the coloured  $c\bar{c}$  pair through nuclear matter; nothing is known experimentally about the interaction of fully formed charmonia with the nuclear medium.

This lack of information is particularly serious if one wants to use charmonium production as a probe for deconfinement in nucleus-nucleus collisions. It was predicted [2] that quark-gluon plasma formation leads to  $J/\psi$  suppression in nuclear collisions, and such a suppression was subsequently in fact observed [3]. This observation in turn triggered a “conventional” explanation [4], in which the suppression was attributed to absorption of the  $J/\psi$  in a dense hadronic (and hence confined) medium. More recently it was shown [5] that the theory of heavy quarkonium interactions with light hadrons leads to a break-up cross section which rules out such an absorption. It was also noted, however, that a direct experimental test of the crucial cross section behaviour is still lacking. The theory on which it is based becomes exact in the heavy quark limit, and although some related checks were favorable, it is certainly necessary to verify experimentally that the charm quark mass is already sufficiently heavy. In the second part of this note, we compare the predictions of heavy quark QCD with previous geometric estimates, in which the QCD threshold behaviour had not been taken into account. From this comparison it becomes clear that an experimental verification of the predicted  $J/\psi$ -nucleon cross section behaviour is possible. After a discussion of possible initial state modifications (EMC effect) we then specify the kinematic range and further aspects of an experiment specifically devoted to this question.

## 2. Production Kinematics

The time needed by the colour octet  $c\bar{c}$  state to become colour neutral can be estimated in terms of the energy of a further gluon “evaporated” to produce a colour singlet state [6]. In the rest frame of the  $c\bar{c}$ , this time  $\tau_0$  becomes

$$\tau_0 = \frac{1}{\sqrt{2m_c\omega}}; \quad (1)$$

$m_c$  is the charm quark mass and  $\omega$  the gluon energy. In confined matter,  $\omega \gtrsim \Lambda_{\text{QCD}}$ , making the colour neutralisation time in the rest frame of the  $c\bar{c}$  pair  $\tau_0 \simeq 0.25$  fm. In the rest frame of the nucleus, the  $c\bar{c}$  travels in the time  $\tau_0$  the distance

$$d_0 = \left( \frac{P_A}{M} \right) \tau_0, \quad (2)$$

with  $P_A$  denoting the momentum and  $M$  the mass of the  $c\bar{c}$  state. From Eq. (2) it is thus clear that sufficiently fast  $c\bar{c}$  are still coloured when they leave the nuclear environment.

The Feynman variable  $x_F$  of the charmonium state and hence of the corresponding  $c\bar{c}$  is

$$x_F \equiv \left( \frac{P}{P_{max}} \right), \quad (3)$$

where

$$P = \gamma P_A - \gamma\beta\sqrt{P_A^2 + M^2} \quad (4)$$

is the center of mass (cms) momentum of the  $c\bar{c}$ ;  $\gamma$  and  $\beta$  specify the transformation from the nuclear rest frame to the cms. The maximum cms momentum the  $c\bar{c}$  can have is determined by the relation

$$s = (\sqrt{P_{max}^2 + M^2} + \sqrt{P_{max}^2 + 4m^2})^2, \quad (5)$$

with  $s$  for the squared incident cms energy and  $m$  for the nucleon mass; Eq. (5) corresponds to the configuration of both nucleons going forward and the  $c\bar{c}$  backward.

We shall now consider the specific case of a 160 GeV/c proton beam incident on a nuclear target, corresponding to  $\sqrt{s} = 17.4$  GeV. At this energy, it is possible to study  $p - A$  collisions at the CERN-SPS with a nuclear beam incident on a hydrogen target as well as the conventional inverse. In Table 1, we list the resulting windows for the production of  $J/\psi$ ,  $\chi_c$  and  $\psi'$ . We thus obtain 8.3 GeV as the maximum momentum which a  $J/\psi$  can have in the cms; this means that in the nuclear rest frame, it has a minimum momentum of 4.7 GeV. In terms of rapidity, the  $J/\psi$  production range at this energy is  $|y_{\text{cms}}| \leq 1.7$ ; in the region between  $|y_{\text{cms}}| = 1.7$  and the maximum rapidity  $|y_{\text{cms}}| = 2.9$ ,  $J/\psi$  production is kinematically not possible.

Since we want to study the interaction of physical charmonium states with the nuclear medium, we want to avoid the kinematic regime in which the  $c\bar{c}$  can interact

with the nucleus already in its colour octet phase. Hence we require  $d_0 \leq 1.5$  fm, so that the  $c\bar{c}$  has become colourless before it leaves the range of the nucleon on which it was produced. Using the above relations, this implies at the noted collision energy  $x_F \lesssim -0.2$ ; for all larger  $x_F$ , at least a partial colour interaction with the nuclear medium remains. In the region  $-0.2 \leq x_F \leq 0$ , this is effectively negligible, since the distance the  $c\bar{c}$  travels as coloured state is only about 2 fm at  $x_F = 0$ . The colour phase increases rapidly with increasing  $x_F$ , and for  $x_F \gtrsim 0.2$ , the  $c\bar{c}$  is coloured on its entire path through the nucleus [6]. Hence the nuclear effects on  $J/\psi$  and  $\psi'$  observed in this region must be identical. As already mentioned, all presently available data [7,8] on charmonium production in hadron-nucleus collisions fall into this region, and they in fact observe the same nuclear suppression of  $J/\psi$  and  $\psi'$  production.

If we wish to study the interaction of fully formed physical resonances with a nuclear medium, it is clear then that we must require  $x_F \leq -0.2$ ; this is a necessary, not a sufficient condition. For the latter, we have to assure that the  $c\bar{c}$  has not only lost its colour, but that it has also had sufficient time to attain its full physical size. An estimate of the resonance formation time  $\tau_r$  for the  $J/\psi$  is obtained from potential theory [9], with  $\tau_r(J/\psi) \simeq 0.35$  fm; this agrees with the rather model-independent upper bound based on the uncertainty relation and the separation between ground state and first excited state. The  $\chi_c$  and  $\psi'$  values are larger; the noted potential theory studies are in accord with about 1 fm for both. With these values and the relation

$$d_r = \left( \frac{P_A}{M} \right) \tau_r, \quad (6)$$

we find that the  $J/\psi$  passes through the entire nuclear medium as a fully formed resonance for  $x_F \lesssim -0.45$ , but that at the energy under consideration the  $\chi_c$  and  $\psi'$  never reach that stage. Although they become colourless in the medium when  $x_F \leq -0.2$ , they have not quite reached full physical size when leaving the medium even for  $x_f \simeq -1$ .

### 3. Charmonium Absorption

The effect of the nuclear medium on the passing coloured  $c\bar{c}$  state has been measured at two different energies [7,8]; it can be understood in terms of the energy loss of the colour octet in a confined medium [6] together with quantum-mechanical coherence effects (nuclear shadowing) [10]. The results are schematically illustrated in Fig. 2 in the range  $x_F \geq 0.1$ ; as noted, the effects on  $J/\psi$ ,  $\chi_c$  and  $\psi'$  are identical. Below  $x_F = 0$ , the  $c\bar{c}$  passes the nucleus in part as a colourless state, and below  $x_F \simeq -0.2$ , it is colourless on its entire path through the nucleus. We can parametrise the survival probability for state  $i$  ( $i = J/\psi, \chi_c, \psi'$ ) as

$$S_i = \exp\{-n_0 \sigma_i L\}, \quad (7)$$

where  $n_0 = 0.17 \text{ fm}^{-3}$  is the normal nuclear density,  $L = (3/4)R_A = (3/4)1.15 A^{1/3}$  the average path length in the nucleus and  $\sigma_i$  the absorption cross section of the state

$i$  in nuclear matter.\* If the charmonium state is fully formed before it leaves the range of the nucleon at which it was produced,  $\sigma_i$  is simply the charmonium-nucleon cross section. If it is not yet fully formed, the effective cross section will be smaller, vanishing in the colour transparency limit of a pointlike colour singlet  $c\bar{c}$  state. In principle, the interaction of this evolving resonance should be studied quantum-mechanically. Here we shall for simplicity parametrise the cross section as function of the distance  $d$  which the state has travelled [12,13], so that

$$\sigma_i(d) = \sigma_i \left( \frac{d}{\bar{L}_i} \right)^2, \quad (8)$$

where  $\sigma_i$  is the fully developed cross section and  $\bar{L} = [(P_A/M_i)\tau_r^{(i)} - 1]$  the effective distance travelled until full resonance formation. Eq. (8) holds for  $d \leq \bar{L}$ ; for  $d \geq \bar{L}$ ,  $\sigma_i(d) = \sigma_i$ . Using this parametrisation, Eq. (7) is replaced by

$$S_i = \exp\left\{-n_0\sigma_i\left[L - \frac{2}{3}\bar{L}_i\right]\right\} \quad (9)$$

whenever  $d \leq \bar{L}$ . To determine the actual survival probabilities, we now still need the cross sections  $\sigma_i$  for the fully formed resonances colliding with nucleons.

In the geometric approach to charmonium absorption,  $\sigma_i$  is assumed to be the total *high energy* collision cross section. This can be estimated by geometric arguments [17], giving  $\sigma_{J/\psi} \simeq 2.5$  mb,  $\sigma_{\chi_c} \simeq 6.0$  mb and  $\sigma_{\psi'} \simeq 9.2$  mb. With this, the picture is complete: for each value of  $x_F$ , we have the corresponding momentum  $P_A$  in the nuclear rest frame; from that we get in turn the distance travelled in the medium as nascent resonance and the associated cross section. The difference in asymptotic cross sections and the different formation times then lead to the absorption patterns shown in Fig. 2 for negative  $x_F$ . The region around  $x_F = 0$  is drawn as continuous interpolation of the forms at positive and negative  $x_F$ .

The crucial assumption leading to the behaviour just discussed is that the cross sections for the interaction of charmonium states with nucleons attain their full asymptotic values at threshold. The invariant energy  $\sqrt{s}$  for the quarkonium-nucleon interaction is below 8 - 9 GeV for the region of  $x_F \leq 0$ ; for  $x_F \leq -0.5$ ,  $\sqrt{s} \leq 6$  GeV. The threshold for  $D\bar{D}$  production in charmonium-nucleon interactions is 4.7 GeV. Hence it is the inelastic cross section *near threshold* that matters for the survival probability at negative  $x_F$ . For the  $J/\psi$ , and perhaps also for the  $\chi_c$ , this cross section is calculable by short distance QCD [14–16][5]. A break-up requires the interaction with hard gluons, but

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\* We note here that if the form (7) is used to parametrise the nuclear suppression of charmonium production at positive  $x_F$  [11], then  $\sigma_i$  becomes the  $i$ -independent cross section for the interaction of a colour octet  $c\bar{c}$  with a nucleon. This can be quite large, but it is not related to that for the interaction of physical quarkonium states with nucleons.

gluons confined to slow hadrons in the charmonium rest frame are generally very soft. As a consequence, the break-up cross sections near threshold are expected to be much smaller than their asymptotic values. For the  $J/\psi$ , the heavy quark theory predicts [5]

$$\sigma_{J/\psi N}(\bar{s}) \simeq 2.5 \text{ mb} \times \left( 1 - \left[ \frac{2M_{J/\psi}(m + \epsilon_{J/\psi})}{(\bar{s} - M_{J/\psi}^2)} \right] \right)^{6.5}, \quad (10)$$

where  $\epsilon_{J/\psi} = 2M_D - M_{J/\psi} \simeq 0.64 \text{ GeV}$  is the  $J/\psi$  binding energy and  $m$  the nucleon mass. The behaviour of this cross section is shown in Fig. 3 as function of the momentum  $P_N$  of a nucleon incident on a  $J/\psi$  at rest. For  $P_N \simeq 4 \text{ GeV}/c$ , corresponding to  $\sqrt{\bar{s}} = 6 \text{ GeV}$ , it is almost two orders of magnitude below its asymptotic value. For a cross section of this size, the survival probability is in good approximation unity, and that is the basis of the prediction that confined matter is transparent for  $J/\psi$ 's.

The theoretical basis for the use of short distance QCD is much less reliable for the  $\chi_c$ , since here the binding energy is just around  $\Lambda_{\text{QCD}}$ . Keeping this in mind, we shall nevertheless see what a corresponding analysis leads to. Instead of Eq. (10) we now obtain

$$\sigma_{\chi N}(\bar{s}) \simeq 11.3 \text{ mb} \times \left( 1 - \left[ \frac{2M_\chi(m + \epsilon_\chi)}{(\bar{s} - M_\chi^2)} \right] \right)^{6.5}, \quad (11)$$

where  $\epsilon_\chi = 2M_D - M_\chi \simeq 0.24 \text{ GeV}$  now denotes the binding energy of the  $\chi_c$ . The asymptotic value is a factor two larger than the geometric estimate; this is a consequence of the fact that short distance QCD [14,15] leads to higher powers in the bound state radii than just  $r^2$ . The behaviour of the  $\chi_c N$  cross section (11) is also shown in Fig. 3.

The  $\psi'$  state lies essentially at the open charm threshold and hence has a binding energy much less than  $\Lambda_{\text{QCD}}$ ; it is therefore definitely not calculable in short distance QCD. The asymptotic form  $\psi'_\infty$  shown in Fig. 2 may thus be a reasonable estimate here.

The resulting survival probabilities  $S_{J/\psi}(x_F)$  and  $S_\chi(x_F)$  are compared in Fig. 2 to those obtained above in the geometric approach. In the region around  $x_F = 0$  we again make an estimate taking into account both the vanishing of the colour interaction with decreasing  $x_F$  and the growing charmonium-nucleon cross section with increasing  $x_F$ .

#### 4. EMC Effect

The survival probabilities shown in Fig. 2 are related to the measured  $p - A$  and  $p - p$  production cross sections through

$$\frac{(d\sigma_i^{pA}/dx_F)}{A(d\sigma_i^{pp}/dx_F)} = \frac{g_A(x_2)}{g_p(x_2)} S_i(x_F) \equiv R_{A/p}(x_2) S_i(x_F), \quad (12)$$

where  $g_A(x_2)$  and  $g_p(x_2)$  are the parton distribution functions in nuclear and proton target, respectively. The fractional parton momentum  $x_2$  is given by

$$x_2 = \frac{1}{2}(\sqrt{(x_F^2 + (4M_i^2/s))} \pm x_F) \quad (13)$$

in terms of the variables  $x_F$  and  $s$ ; the plus sign holds for positive, the minus sign for negative  $x_F$ . At the energy under discussion above ( $\sqrt{s} = 17.4$  GeV) and for  $x_F \leq 0$ , we have  $x_2 \geq 0.15$ ; we are thus above the region in which quantum-mechanical coherence effects (nuclear shadowing or antishadowing) play a role [10]. However, we know from deep inelastic scattering on nuclear targets that for  $x_2 \geq 0.15$  the quark parton distributions in nuclei are modified in comparison to those in nucleons. This modification, generally denoted as EMC effect [18], is shown in Fig. 4.

Although the EMC effect has so far been observed only for quarks, it is to be expected that gluons will exhibit a similar behaviour, so that the initial state factor  $R_{A/p}(x_2)$  will introduce a further  $x_F$  variation in addition to that coming from  $S_i(x_F)$ . With increasing  $|x_F|$ , charmonium production is more and more due to quark-antiquark annihilation rather than to gluon fusion; the two contributions become approximately equal around  $|x_F| = 0.5$ , and as  $|x_F| \rightarrow 1$ , the  $q\bar{q}$  contribution is dominant [1,19]. We shall here assume that quark and gluon distributions behave in the same way and use the quark form of  $R_{A/p}$  in the whole region  $-1.0 \leq x_F \leq 0$ ; this gives us a prediction for the behaviour of the cross section ratio in that region. It is illustrated in Fig. 5 for the directly produced  $J/\psi$  state in the two cases considered.

As a cross check of the form of  $R_{A/p}(x_2)$ , the EMC effect in this region can also be studied independently. Measuring Drell-Yan dilepton production there provides  $R_{A/p}(x_2)$  for quarks directly, without any final state modification. A measurement of open charm production leads to  $R_{A/p}(x_2)$  in just the same superposition of quark-antiquark annihilation and gluon fusion as in charmonium production, but again without any final state effect. Separate measurements of Drell-Yan and/or open charm production would thus determine the EMC modification without additional final state effects. Such measurements can therefore be used to remove the EMC modification of  $J/\psi$  and  $\psi'$  production data, which can then be compared directly to the predictions shown in Fig. 2.

Such measurements would moreover be of considerable interest in themselves. At positive  $x_F$ , little or no nuclear modifications are seen in Drell-Yan production [20]. The same experiment also showed no nuclear effects on open charm production. These two facts are part of the empirical basis for the claim [10] that the considerable suppression of charmonium production in  $p-A$  collisions at positive  $x_F$  is due to quantum-mechanical coherence effects and energy loss suffered by the passing virtual colour charge, and not to factorisable parton distribution function changes. The measurement of factorisable modifications for negative  $x_F$  would provide further support to this interpretation.

## 5. Experimental Aspects

The study of charmonia or Drell-Yan dileptons slow in the nuclear rest frame has up to now been essentially impossible. Both require the detection of slow dileptons, and for this the abundance of slow hadrons constitutes an overwhelming background. In the case of fast dileptons, a hadron absorber can eliminate these, and hence all  $p-A$

studies were restricted to dilepton pairs of more than 20 GeV in the rest frame of the nuclear target. This in turn restricts the available data to  $x_F \gtrsim 0$ .

The advent of the  $Pb$ -beam at the CERN-SPS has removed this constraint. With the  $Pb$ -beam incident on a hydrogen (or deuterium) target, the nuclear rest frame moves with a lab momentum of 160 GeV. Hence now charmonia and their decay dileptons are very fast in the lab system and will thus pass the hadron absorber. The window for such measurements is evident from Table 1, and the expected behaviour for positive  $x_F$  is that shown in Figs. 2 for negative  $x_F$ . For clarity, we denote the variables in the case of a  $A$ -beam incident on a hydrogen target by a superscript  $A$ . Thus the region of greatest interest is  $0.4 \geq x_F^A \geq 1$ ; in terms of rapidity, this corresponds to the range  $3.6 \geq y_{\text{lab}}^A \geq 4.5$ .

The above predictions for  $J/\psi$  production correspond to directly produced  $1S$   $c\bar{c}$  resonances. The  $J/\psi$  peak observed in the measured dilepton spectrum is about 60% due to this origin and about 40% due to direct  $\chi_c$  production with subsequent decay  $\chi_c \rightarrow J/\psi + \gamma$  (see [1]). Unless it is possible to measure  $\chi_c$  production independently [21], the data will contain a superposition of direct  $1S$   $J/\psi$  production and  $J/\psi$ 's from  $\chi_c$  decay.\* To estimate the effect of this in the two scenarios considered here, we simply add the corresponding predictions with the noted 60/40 weights; the result is shown in Fig. 6. As seen, for  $x_F \leq -0.4$ , the two approaches differ qualitatively in their functional form and quantitatively by more than 20%. An experimental test should therefore be possible.

Finally we note that the analysis proposed here is a comparison of production data from a heavy nuclear beam on a hydrogen or deuterium target with that from a proton beam on the same target. Although there are measurements for the latter (see [1] for a compilation), it seems very desirable to obtain both  $A$  and  $p$  beam data in the same experiment, in order to avoid acceptance uncertainties.

## 6. Conclusions

The study of charmonium production at low momenta in the nuclear rest frame, together with that of Drell-Yan dileptons and open charm, opens a completely unexplored region of the behaviour of hard probes in nuclear matter. Such studies have become experimentally feasible only with the advent of the  $Pb$ -beam at the CERN-SPS, and since they require very forward measurements, they would not be easy to carry out in future collider experiments. The results of such a program would have a decisive impact on at least three different topics:

- They would test directly the heavy quark theory prediction of strong threshold damping for the interaction of  $J/\psi$ 's with light hadrons. This is crucial for the use of charmonium production as deconfinement probe.

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\* In addition, a few percent ( $\sim 5$  %) will come from  $\psi'$  decays. We neglect this in both scenarios.



- They would allow a study of the EMC effect by  $c\bar{c}$  production and thus provide a complementary tool to deep inelastic scattering on nuclear targets. This is important for the investigation of nuclear modifications of parton distributions.
- By comparing nuclear effects on charmonia with those on Drell-Yan production, the role of modified parton distributions could be tested directly. Fast  $c\bar{c}$  pairs (in the nuclear rest frame) show a very different behaviour than fast dileptons, and this rules out the factorisable modification of parton distributions there. For slow  $c\bar{c}$  and dileptons, the behaviour is predicted to be similar and the modifications factorisable.

The experimental investigation of  $Pb - p$  collisions could thus do much to further our understanding of the effect of a confined (nuclear) medium on the parton structure of hadronic systems.

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**Table 1:**

Windows for Charmonium Production in  $p - A$  Collisions at  $\sqrt{s} = 17.4$  GeV

Variable	$J/\psi$	$\chi_c$	$\psi'$
$ P_{\text{CMS}}^{\text{max}} $ [GeV]	8.31	8.24	8.19
$ y_{\text{CMS}}^{\text{max}} $	1.71	1.59	1.54
$P_A^{\text{min}}$ [GeV]	4.70	6.12	6.89
$y_A^{\text{min}}$	1.21	1.33	1.38
$y_{\text{lab}}^{\text{max}}$	4.63	4.51	4.45

## Figure Captions

Fig. 1:  $J/\psi$  production by gluon fusion (a) and by quark-antiquark annihilation (b).

Fig. 2: Charmonium production in  $p - Pb$  collisions at 160 GeV incident beam energy. The suppression for  $x_F \geq 0$  is the same for  $J/\psi$ ,  $\psi'$  and  $\chi_c$ ; data are for  $J/\psi$  production at 200 GeV beam energy [7]. The predicted suppression for  $x_F \leq 0$  is shown for asymptotic cross sections (solid lines) and for cross sections from short distance QCD (dashed lines).

Fig. 3: Dissociation cross sections for  $J/\psi$ -nucleon and  $\chi_c$ -nucleon interactions as function of the momentum  $P_N$  of a nucleon incident on a charmonium at rest.

Fig. 4: EMC effect: ratio  $R_{A/p} = g_A(x)/g_p(x)$  of quark distribution function  $g_A(x)$  in heavy nuclei to that in nucleons  $g_p(x)$  [18].

Fig. 5: Direct  $J/\psi$  production in  $p - Pb$  collisions in the geometric approach and from short distance QCD, with (solid line) and without (dashed line) EMC effect modification.

Fig. 6:  $J/\psi$  production in  $p - Pb$  collisions in the geometric scenario and in short distance QCD, with 40% of the observed  $J/\psi$  coming from  $\chi_c$  decay; without EMC effect.

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